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Analysis

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Cost-effective adaptation strategies to rising river flood risk in Europe

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Supplementary Information

Summary

S1. Additional details on Methods

S1.1 Climate projections

Table S1. Regional climate projections used in river flood impact analysis and corresponding year of exceeding 1.5, 2 and 3°C warming. Years are calculated using a 30-year moving average of surface air temperature. For the description of the climate models see [1].

RCM (R)	Driving GCM (G)	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
		1.5 °C		2 °C		3 °C	
CCLM4.8-17	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044		2067
	ICHEC-EC-EARTH	2033	2026	2056	2041		2066
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044		2067
HIRHAM5	ICHEC-EC-EARTH	2032	2028	2054	2043		2065
WRF331F	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035		2054
RACMO22E	ICHEC-EC-EARTH	2032	2026	2056	2042		2065
RCA4	CNRM-CERFACS-CNRM-CM5	2035	2029	2057	2044		2067
	ICHEC-EC-EARTH	2033	2026	2056	2041		2066
	IPSL-IPSL-CM5A-MR	2023	2021	2042	2035		2054
	MOHC-HadGEM2-ES	2021	2018	2037	2030	2069	2051
	MPI-M-MPI-ESM-LR	2034	2028	2064	2044		2067

S1.2 Data collection for adaptation modelling

For the adaptation analysis, we constructed a database of flood risk reduction investments based on a review of scientific, grey and technical literature. The database provides an overview of the main types of investments applied in case studies, mainly in Europe [2,3,4,5]. We used information on size and cost of past applications in literature to derive unit costs of adaptation measures suitable for application within a pan-European framework (e.g. the cost to increase the height of one linear kilometre of dyke by one meter). We also compiled information to clarify the link between implementation costs and impact reduction (e.g. damage reduction factors reported for specific flood-proofing measures). Table S2 summarizes the unit costs derived from the database of adaptation measures.

We include in the adaptation analysis only measures for which we found sufficient and robust information on quantitative costs (especially unit costs) and performance estimates. Other risk reduction measures are not considered because information was insufficient, or because they were deemed not suitable for the scope of the study. For instance, flood early warning systems (EWSs) are used in several countries and river basins in Europe, but the studies evaluating their cost effectiveness are limited and with contrasting findings. Pappenberger et al. [6] estimated a monetary benefit of the order of 400€ for every 1€ invested in continental-scale flood early warning systems (EWSs). However, other studies [7] calculated much lower cost-to-benefit ratios for a local-scale EWS. Furthermore, we could not find studies providing unit costs (e.g. based on the extension of the river network to be monitored) for setting up or improving existing EWSs.

Table S2. Summary of unit costs derived from the database of adaptation measures. The table reports also the damage reduction ratios for flood-proofing measures for buildings. For the details on how to access the complete database see the Data Availability section.

Normalized unit cost (2015)					
		Average	25% percentile	median	75% percentile
Dike systems reinforcement	€/m/m	6405	1829	3941	9514
Detention areas	€/m3	3.73	1.05	3.59	5.00
Flood-proofing measures	€/m2	376	156	270	493
Relocation	€/m2	1373	906	1252	1826
Damage reduction ratio (average)					
		Average	25% percentile	median	75% percentile
Flood-proofing measures	(-)	41%	10%	37%	80%

Dams and reservoirs are traditional flood control measures and are widely used in Europe [8]. The current LISFLOOD hydrological setup includes more than 1400 reservoirs and 200 lakes across Europe, which are modelled using a two-parameter approach that regulates outflow considering inflow and stored volume (https://ec-jrc.github.io/lisflood-model/, last access on 12 July 2022). While the effect of existing structures is considered in the hydrological model, we do not consider the building of new structures as a possible adaptation measure and focus only on exploiting natural retention and detention in floodplains. This is done for a number of reasons:

- Flood control dams and reservoirs are site-dependent and highly engineered structures, meaning that simulating their design (e.g. dimensioning, estimation of costs, design of operating rules) is not suitable for a continental-scale study.
- Flood control dams and reservoirs are typically in-line structures that modify the flow regime in all conditions, but the operating rules of existing structures are generally not known. Simulating new dams would require reproducing the combined effects of existing and new protection structures, adding further large uncertainty to the modelling framework (see Section S4 for a more detailed discussion).
- Traditional flood control reservoirs have high costs, negatively impact ecosystems and may create societal stresses [8,9]. Conversely, here we are interested in disentangling how using the storage potential of floodplains can reduce flood risk through a more spatially-distributed approach, while minimizing local negative impacts.

S1.3 Modelling of the adaptation measures

Detention areas

River detention areas (or basins) are areas located along river channels designed to temporarily retain floodwater volumes, thus reducing and delaying peak flows during extreme events [4]. Detention areas are generally surrounded by a dike and capture floodwater above a pre-defined water level through control devices (a pipe or a spillway), while other outlet structures are used to release water back in the river channel. Areas designed to permanently retain some volume of water at all times are usually called retention basins, even though in scientific literature there is some overlap on the definition of retention and detention. Here we assume that floodwater is stored temporarily, even though permanent storage might be viable in some cases. Detention and retention areas can be considered as nature-based solutions because they leverage the storage potential of natural floodplains [10], complementing it with structures to allow for safe income, storage and outgoing of floodwaters.

Flood proofing measures

Flood-proofing measures are structural and non-structural modifications of buildings aimed at preventing or minimizing flood damage to structures and/or their contents [11,12]. Dry flood proofing aims at making a building impermeable to floodwaters up to the expected floodwater height (e.g. waterproof sealing of the cellar). Wet flood proofing measures allow flooding of the structure and reduce damages by means of flood-adapted use and equipment of buildings (e.g. usage of waterproofed building material and movable furniture). Flood proofing measures applicable depend on local flood and exposure characteristics (e.g. expected range of flood water depths, type and structure of the building to be protected). Most research works on these measures provide an overview of costs and benefits for specific case studies [4,12], and few studies report analytical analyses of different measures on real cases [13] or standardized buildings [14].

S1.4 Sensitivity analysis

The sensitivity analysis of the modelling framework is carried out by performing multiple runs with different combinations of parameter values and modelling assumptions. We take into account the uncertainty in i) climate projections, ii) hydrological-hydraulic modelling, iii) damage calculations and iv) adaptation costs, as outlined in the following subsections.

Climate projections

Projections of future climate conditions are inherently uncertain, and constitute one of the most considered sources of uncertainty in flood risk modelling studies [15,16]. For climate projections, an ensemble of models is essential, due to the atmosphere being a chaotic system. This allows testing the importance of different model structures and parameterizations, assuming that the ensemble is representative of the domain of possible future conditions. This is taken into account here by using the ensemble of climate projections from EURO-CORDEX [1] listed in Table S1.

Flood hazard modelling

Hydrological and hydraulic modelling might contribute as much as the climate forcing to the overall uncertainty of river flood risk estimates [16,17]. Contrary to the ensemble approach for climate forcing, high-resolution ensembles of hydrological-hydraulic models forced by EURO-CORDEX are not available for Europe. Therefore, we examined the parameters and modelling assumptions that are more likely to influence the overall uncertainty of the outcomes. Dottori et al. [18] listed several uncertainty sources that might influence the estimation of flood frequency, magnitude and extent (such as extreme value distribution fitting, characterization of input hydrographs, topographic data, model calibration). The same authors found that flood extent maps have limited sensitivity to the magnitude of peak discharges and to the use of different elevation datasets, due to the simplified representation of river channels and flood defences.

On the other hand, flood protections are crucial in determining overall flood risk in our modelling framework. The cut-off between a flood happening or not is based on comparing frequencies of extreme events with the design standard of flood defences, which are known only in few countries and regions (see Section S3). As such, we opt for including both flood modelling uncertainty and uncertainty in flood protection in a single parameter, which is the estimated level of flood protection. Specifically, we produce alternative maps of protection standards by increasing/reducing by 50% the design return periods for all catchments in Europe, and calculate resulting impacts for each of these protection scenarios. Note that in this way we account for additional uncertainty factors, such as the over-/under-estimation of reported design standards, and the effects of defence failures (not considered in our analysis).

Economic impacts

Estimates of flood impacts are affected by considerable uncertainty even when using local scale data and detailed loss models, and continental-scale estimations are no exception [19,20]. We explore the sensitivity of flood impacts considering the uncertainty related to flood damage functions. To this end, we calculate economic losses using the 5th, 50th (median) and 95th percentiles of maximum damage values reported by [21]. We therefore assume that the uncertainty on the maximum damage can represent all other uncertainty sources not explicitly represented, such as the shape of normalized curves and the GDP/construction costs linkage [21]. Note that in the analysis we do not consider indirect economic costs associated to business interruptions, emergency measures and others. We also disregard the uncertainty on population and land-use distribution, assuming that they are less relevant than other sources of uncertainty considered.

Adaptation costs

The analysis of literature shows that implementation costs are largely variable due to several factors (e.g. type of measure adopted, location, effectiveness). To provide a sample of the sensitivity of results to adaptation costs, we consider three scenarios using the 25th, 50th (median) and 75th percentiles of the empirical distribution derived from the database of adaptation measures (see Section S1.2). Note that we did not use 5th/95th percentiles to increase the robustness of estimations, because of the limited amount of data entries available for each measure. Also, we do not consider other sources of uncertainty such as the effectiveness of flood-proofing measures in reducing damage (see Section S4 for further discussion).

Scenarios considered

All the scenarios listed in the previous subsections are combined together assuming that the four main sources of uncertainty are independent from each other. Therefore, we consider a total of 1485 simulations, obtained by combining 22 climate forcing scenarios (11 climate models x2 RCP scenarios), 3 warming levels, 3 flood protection scenarios, 3 damage model scenarios and 3 adaptation cost scenarios.

We further assume a complete spatial dependence of the parameter uncertainty over the continent, with the exception of parameters derived from climate models. For instance, the scenarios based on the 95th percentile of maximum damage assume that damage is estimated everywhere using the local 95th percentile value. We take such assumption because it was not possible to determine the spatial correlation of parameter values, except for the climate model ensemble where spatial correlations directly derive from model results. This is a penalizing assumption for the modelling framework because the resulting uncertainty ranges are broadly similar at local and continental scale. Assuming some degree of spatial independence of parameter values (i.e. the hazard model bias is correlated at local/regional scale but not at broader scale) would likely narrow the uncertainty range at continental scale, while leaving comparable uncertainty ranges at local/regional scale [22]. For this reason, we present model outcomes using the interquartile range rather than the 90% confidence interval.

Note that in our sensitivity analysis we disregard uncertainty due to socio-economic scenarios. This is done because, on the one hand, socio-economic projections for Europe applied here do not include uncertainty estimations [23,24]; on the other hand, global scenarios derived from Shared Socio-economic Pathways (SSPs) have much coarser spatial resolution and therefore are not suitable to estimate uncertainty at European scale. Nevertheless, we believe that the overall number of scenarios included is sufficient to show the robustness of the outcomes of the risk and adaptation analysis.

S2. Supplementary results

Table S3. Summary of the expected annual damage (EAD) in million € (2015 values) for all the countries of the study area and for the whole study area (EU+UK, in bold), under present conditions (base), and for the year 2100 under future socioeconomic conditions and climate scenarios (1.5°C, 2°C, 3°C warming). For each climate scenario the table provides the ensemble median (med) and the first/third quartile (Q1-Q3).

	baseline		1.5°C		2°C		3°C	
Country	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	274	175-427	737	487-1094	755	471-1274	1019	668-1774
Belgium	219	139-338	711	431-1063	972	615-1472	1466	830-2316
Bulgaria	87	58-129	187	122-279	220	130-360	295	165-500
Croatia	181	123-273	543	364-768	724	471-1088	927	627-1375
Cyprus	4	3-7	8	5-11	7	4-11	5	3-8
Czechia	418	277-668	1045	699-1635	1324	843-2043	1883	1002-3197
Denmark	14	9-23	39	26-58	51	34-79	76	49-127
Estonia	56	37-87	111	67-165	123	62-230	151	78-283
Finland	227	151-392	528	340-836	758	399-1266	901	463-1716
France	1291	816-2104	4420	2837-6962	6471	4148-10018	8007	5121-11490
Germany	930	569-1500	2812	1841-4189	3671	2408-5993	5330	3238-8302
Greece	76	50-122	109	74-163	124	76-209	156	83-312
Hungary	265	169-413	807	530-1210	1129	640-1786	1803	991-3142
Ireland	62	38-103	199	130-292	248	162-370	482	304-748
Italy	876	610-1314	2503	1626-3564	2806	1833-4359	4335	2759-6718
Latvia	220	133-338	452	296-673	506	304-860	626	360-1223
Lithuania	111	70-176	223	149-330	254	142-437	294	160-581
Luxembourg	18	10-31	57	36-90	79	47-138	99	57-155
Netherlands	74	49-117	252	150-449	415	216-809	530	279-1235
Poland	590	382-898	1394	933-2004	1698	1089-2609	2317	1508-3746
Portugal	53	33-86	85	52-126	85	56-129	82	45-127
Romania	334	205-547	840	564-1243	1091	662-1729	1637	846-2572
Slovakia	148	97-224	420	279-608	499	310-745	685	407-1113
Slovenia	61	41-90	149	101-225	205	130-311	282	179-447
Spain	479	322-710	957	636-1426	977	629-1500	1055	676-1563
Sweden	231	141-369	771	502-1204	1337	759-2303	2281	1180-4686
UK	687	467-1011	2155	1401-3038	2668	1786-4133	4621	3066-6856
EU-27 + UK	7645	5672-11205	23005	15371-33232	30999	21620-44902	43609	30431-61422

Table S4. Summary of the expected annual population exposed (EAPE) in thousand people for all the countries of the study area and for the whole study area (EU+UK, in bold), under present conditions (base), and for the year 2100 under future socioeconomic conditions and climate scenarios (1.5°C, 2°C, 3°C warming). For each climate scenario the table provides the ensemble median (med) and the first/third quartile (Q1-Q3).

	baseline		1.5°C		2°C		3°C	
Country	**med**	**Q1-Q3**	**med**	**Q1-Q3**	**med**	**Q1-Q3**	**med**	**Q1-Q3**
Austria	4.1	2.7-6.2	6.0	4.3-9.6	6.7	4.1-10	8.4	5.9-12.4
Belgium	3.9	2.6-6.3	8.8	6.6-14.4	12.4	8.4-19.3	19.5	13.1-31.9
Bulgaria	2.9	2-4.3	1.9	1.4-3.1	2.5	1.4-4	2.9	2.1-5.8
Croatia	4.6	3.3-7.2	7.1	5.6-11.4	10.4	7.6-15.4	14.3	11.4-22.9
Cyprus	0.0	0-0	0.0	0-0	0.0	0-0	0.0	0-0
Czechia	6.9	4.8-10.4	9.8	7.6-17.6	12.4	9.1-18.7	18.6	11.8-29.1
Denmark	0.1	0.1-0.2	0.2	0.2-0.3	0.3	0.2-0.4	0.5	0.3-0.6
Estonia	0.8	0.5-1.2	0.9	0.6-1.4	1.0	0.5-1.8	1.3	0.6-2.1
Finland	3.2	1.9-5.4	4.0	2.5-5.2	5.0	3.1-8.4	5.5	3.4-12.7
France	21.9	14.3-34.1	49.8	33.9-78.7	74.2	52.9-117.1	88.3	64.7-140.8
Germany	27.3	18.1-46.2	45.4	31.5-67.2	61.9	40.5-84.2	86.7	54.1-132.6
Greece	1.8	1.2-2.6	1.8	1.3-2.7	2.2	1.3-3.3	2.4	1.3-4.4
Hungary	6.4	4.5-10.7	10.3	7.1-14.7	13.6	7.7-21.6	21.6	14-36.7
Ireland	0.9	0.5-1.4	1.6	1.3-2.7	2.0	1.5-3.3	4.5	2.4-5.9
Italy	19.0	14-28.3	31.4	24.4-51.1	40.1	24.5-53.2	60.0	37.8-82.7
Latvia	4.2	2.7-6.3	2.6	1.9-4.6	3.0	2-5.5	3.9	2.5-7.4
Lithuania	1.4	0.9-1.9	1.0	0.7-1.6	1.1	0.7-1.9	1.4	0.8-2.6
Luxembourg	0.1	0.1-0.2	0.4	0.2-0.6	0.5	0.3-0.9	0.7	0.3-1
Netherlands	1.6	1.1-2.3	2.6	1.7-5.1	4.4	2.5-8.7	5.5	3.2-13.9
Poland	18.6	13.1-30.3	20.7	15.1-33	26.6	17.5-39.5	35.7	23.9-54
Portugal	0.8	0.5-1.3	1.1	0.8-1.9	1.2	0.8-1.7	1.2	0.7-1.9
Romania	12.8	8.5-18.4	12.5	9.3-20.1	15.8	11.2-24	22.2	12.8-33.7
Slovakia	3.3	2.2-4.9	3.8	2.8-6.1	4.8	3.5-7	6.9	3.8-9.4
Slovenia	1.0	0.8-1.6	1.4	1-2.2	2.0	1.2-3	2.5	1.9-4.3
Spain	11.1	7.8-19.4	16.7	11.9-29.3	17.0	12-28.7	17.4	12.8-29.7
Sweden	2.1	1.3-3.2	4.8	3-6.9	7.4	4.6-11.3	11.5	7.4-23.9
UK	8.4	6.1-12	16.6	13-28.8	25.6	16-36	45.3	27.9-62.9
EU-27 + UK	166.4	124.3-276.4	257.9	212.5-422.3	364.8	270.3-525	491.1	370.7-735.6

Table S5. Changes in flood impacts in 2100 with respect to present considering only climate change (climate only, 3°C), only socio-economic change (economy only), and both drivers together (climate + economy). Impacts are given at country level and for EU27+UK as expected annual damage (EAD) and population exposed (EAPE). All values refer to the ensemble median.

	Change in expected annual damage - 3°C WL			Change in expected annual population exposed - 3°C WL		
Country	**climate only**	**economy only**	**climate + economy**	**climate only**	**society only**	**climate + society**
Austria	97%	108%	283%	84%	25%	117%
Belgium	244%	119%	562%	255%	80%	398%
Bulgaria	109%	73%	254%	85%	-38%	20%
Croatia	209%	129%	431%	210%	50%	255%
Cyprus	-35%	56%	14%	-43%	219%	107%
Czechia	165%	97%	345%	167%	23%	164%
Denmark	210%	96%	455%	255%	15%	218%
Estonia	62%	86%	251%	63%	7%	90%
Finland	128%	65%	371%	82%	-8%	145%
France	249%	113%	465%	223%	62%	300%
Germany	280%	97%	491%	294%	10%	238%
Greece	67%	36%	164%	47%	8%	85%
Hungary	301%	111%	629%	303%	12%	264%
Ireland	300%	112%	665%	320%	43%	357%
Italy	194%	109%	376%	195%	36%	195%
Latvia	67%	89%	227%	60%	-29%	14%
Lithuania	75%	75%	217%	62%	-28%	22%
Luxembourg	187%	123%	465%	172%	205%	631%
Netherlands	311%	156%	797%	252%	55%	388%
Poland	148%	87%	335%	137%	1%	121%
Portugal	11%	32%	42%	16%	29%	41%
Romania	199%	97%	388%	131%	-12%	75%
Slovakia	190%	100%	376%	195%	-9%	113%
Slovenia	191%	94%	384%	197%	18%	182%
Spain	28%	68%	100%	21%	47%	59%
Sweden	417%	110%	1184%	241%	69%	630%
UK	266%	119%	534%	314%	66%	403%
EU-27 + UK	**203%**	**102%**	**425%**	**190%**	**25%**	**200%**

Table S6. Overview of key adaptation results based on detention areas at country level for the 1.5°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median (med) and the first/third quartile (Q1-Q3).

	Detention areas							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	3.0	2.1-4.7	73%	52%-86%	80%	61%-89%	60	40-108
Belgium	4.2	3-6.8	78%	62%-89%	83%	70%-91%	44	29-78
Bulgaria	2.7	2-3.7	70%	51%-85%	74%	57%-88%	16	10-24
Croatia	3.3	2.1-6.7	89%	79%-94%	92%	84%-96%	49	21-76
Cyprus	0.0	0-0	0%	0%-0%	0%	0%-0%	3	1-3
Czechia	4.1	3.2-5.5	81%	68%-90%	86%	76%-92%	67	48-97
Denmark	3.3	2.2-5.4	85%	69%-92%	89%	78%-94%	3	2-6
Estonia	1.2	0-1.9	13%	0%-61%	19%	0%-72%	2	0-14
Finland	2.7	1.9-3.7	53%	29%-66%	46%	30%-61%	39	19-68
France	3.1	2.3-4.7	74%	58%-85%	81%	69%-90%	358	257-611
Germany	3.5	3.1-4.1	66%	50%-81%	68%	51%-83%	221	136-330
Greece	2.6	1.9-3.6	64%	43%-78%	65%	48%-79%	10	6-15
Hungary	2.7	2-4.4	78%	58%-88%	82%	64%-90%	58	41-100
Ireland	2.4	1.9-3.5	69%	40%-85%	77%	45%-89%	18	10-28
Italy	4.8	3.6-7.6	81%	71%-88%	86%	79%-92%	157	110-252
Latvia	2.9	1.9-4.5	39%	21%-62%	48%	29%-74%	22	5-45
Lithuania	1.7	1.1-2.7	18%	0%-55%	29%	1%-64%	6	0-23
Luxembourg	3.6	2.2-6.4	77%	57%-90%	85%	71%-94%	5	2-8
Netherlands	4.0	2.5-6.2	23%	6%-43%	26%	8%-45%	5	2-12
Poland	2.2	1.9-2.9	57%	33%-75%	60%	36%-79%	122	67-192
Portugal	2.0	1.5-2.5	9%	3%-20%	10%	4%-16%	1	0-4
Romania	2.4	1.9-2.9	43%	27%-65%	51%	34%-67%	51	27-90
Slovakia	3.4	2.5-5.3	78%	58%-88%	83%	63%-91%	28	19-50
Slovenia	2.3	1.7-3.5	74%	50%-87%	78%	54%-90%	12	8-22
Spain	2.1	1.8-2.5	25%	13%-49%	31%	10%-53%	54	20-122
Sweden	2.6	1.9-3.9	52%	30%-68%	55%	38%-70%	55	29-89
United Kingdom	6.5	4.6-11.7	84%	76%-90%	86%	78%-91%	109	62-161
EU+UK	**3.5**	**2.8-4.8**	**68%**	**56%-78%**	**72%**	**60%-82%**	**1641**	**1135-2394**

Table S7. Overview of key adaptation results based on dikes strengthening at country level for the 1.5°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median and the first/third quartile (Q1-Q3).

	Dikes strengthening							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	2.1	1.6-3.2	55%	27%-76%	59%	28%-79%	72	34-114
Belgium	2.9	2.1-4.8	73%	53%-87%	80%	62%-90%	56	37-102
Bulgaria	1.6	1.1-2.2	22%	2%-45%	29%	5%-54%	6	1-19
Croatia	1.6	1.3-2.5	63%	21%-85%	71%	21%-89%	52	21-84
Cyprus	0.0	0-0	0%	0%-0%	0%	0%-0%	0	0-0
Czechia	2.3	2-3	57%	36%-76%	64%	41%-80%	88	48-137
Denmark	1.4	0-2.2	38%	0%-70%	42%	0%-79%	4	0-7
Estonia	1.5	0-2.4	52%	0%-83%	61%	0%-89%	9	0-17
Finland	1.8	1.4-2.6	25%	8%-49%	26%	7%-43%	31	7-60
France	2.2	1.7-2.9	54%	33%-74%	64%	45%-81%	421	239-669
Germany	2.6	2.1-3.2	56%	38%-72%	56%	41%-72%	262	157-409
Greece	1.1	0-1.6	0%	0%-27%	0%	0%-34%	0	0-8
Hungary	2.0	1.4-2.6	37%	12%-65%	39%	13%-68%	43	12-92
Ireland	1.8	1.3-2.4	40%	12%-73%	45%	17%-80%	17	5-32
Italy	2.4	2-3.3	64%	41%-78%	71%	51%-84%	241	153-375
Latvia	2.0	1.3-2.9	55%	30%-81%	67%	36%-89%	39	15-70
Lithuania	1.2	0-1.7	2%	0%-47%	3%	0%-57%	1	0-29
Luxembourg	2.6	1.7-5.1	76%	50%-90%	84%	67%-93%	5	3-10
Netherlands	2.9	1.8-4.7	24%	3%-56%	26%	6%-61%	9	2-17
Poland	1.6	1.3-1.8	13%	4%-34%	15%	5%-37%	43	10-121
Portugal	1.4	0-1.9	4%	0%-14%	3%	0%-8%	1	0-2
Romania	1.9	1.4-2.5	19%	2%-38%	15%	3%-36%	26	3-64
Slovakia	2.4	1.9-3.4	43%	18%-68%	46%	20%-70%	22	9-50
Slovenia	1.5	1.2-2	33%	9%-75%	38%	10%-80%	11	3-22
Spain	1.9	1.6-2.2	9%	5%-17%	6%	3%-14%	21	9-47
Sweden	2.8	1.9-4	38%	17%-55%	39%	19%-53%	41	16-74
United Kingdom	2.8	2.2-4.5	74%	60%-85%	76%	62%-86%	189	132-301
EU+UK	**2.4**	**2-3.1**	**49%**	**34%-66%**	**52%**	**37%-67%**	**1857**	**1139-2930**

Table S8. Overview of key adaptation results based on flood proofing of buildings at country level for the 1.5°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) is calculated as difference in undiscounted damage in 2100 with and without adaptation. Note that reduction in population exposed (EAPE) is not calculated (nc). Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median and the first/third quartile (Q1-Q3).

	Flood proofing of buildings							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	1.8	1.3-3.8	0.0%	0.0%-0.2%	nc	nc	0.0	0-0.9
Belgium	1.9	1.3-24.7	0.0%	0.0%-0.3%	nc	nc	0.0	0-1
Bulgaria	1.8	1.5-2.1	0.3%	0.2%-1.2%	nc	nc	0.1	0.1-0.8
Croatia	2.0	1.6-2.6	0.4%	0.3%-0.5%	nc	nc	0.3	0.3-0.7
Cyprus	0.0	0-1	0.0%	0.0%-0.4%	nc	nc	0.0	0-0
Czechia	1.9	1.6-2.9	0.3%	0.1%-1.2%	nc	nc	0.6	0.1-5.2
Denmark	0.0	0-1.2	0.0%	0.0%-1.2%	nc	nc	0.0	0-0.2
Estonia	2.4	1.7-3.7	0.3%	0.2%-0.8%	nc	nc	0.0	0-0.4
Finland	2.2	1.6-3.3	0.1%	0.1%-0.9%	nc	nc	0.1	0-1.7
France	2.0	1.6-3.1	0.1%	0.0%-0.3%	nc	nc	0.8	0.2-6.4
Germany	3.4	2-5	0.1%	0.1%-0.2%	nc	nc	0.3	0.1-2.5
Greece	3.0	2.4-3.9	0.3%	0.2%-0.4%	nc	nc	0.0	0-0.1
Hungary	1.5	1.1-3.5	0.0%	0.0%-0.2%	nc	nc	0.0	0-0.5
Ireland	1.6	1.5-1.9	0.5%	0.1%-1.8%	nc	nc	0.3	0-1.4
Italy	2.0	1.8-2.2	0.5%	0.3%-3.0%	nc	nc	2.8	1.1-17.5
Latvia	2.1	1.7-2.6	0.3%	0.1%-1.2%	nc	nc	0.3	0.1-1.4
Lithuania	5.5	1.6-12.9	0.2%	0.1%-1.1%	nc	nc	0.0	0-1
Luxembourg	0.0	0-1.4	0.0%	0.0%-0.0%	nc	nc	0.0	0-0
Netherlands	0.0	0-0	0.0%	0.0%-0.0%	nc	nc	0.0	0-0
Poland	3.7	1.8-4.7	0.1%	0.1%-0.4%	nc	nc	0.1	0.1-1.7
Portugal	4.4	3.1-6.1	0.3%	0.2%-0.5%	nc	nc	0.0	0-0.1
Romania	2.6	2.1-3.1	0.7%	0.5%-0.8%	nc	nc	0.8	0.6-1.4
Slovakia	2.6	1.3-4.8	0.0%	0.0%-0.0%	nc	nc	0.0	0-0
Slovenia	3.0	1.9-5.2	0.2%	0.2%-0.4%	nc	nc	0.0	0-0
Spain	3.0	2.6-3.5	1.0%	0.7%-10.8%	nc	nc	1.6	0.8-15.7
Sweden	2.3	1.7-3.1	0.9%	0.2%-2.8%	nc	nc	1.7	0.2-11.3
United Kingdom	2.4	1.9-3.5	6.4%	4.8%-17.1%	nc	nc	16.4	11.7-130.7
EU+UK	2.3	2-2.9	0.9%	0.7%-5.0%	nc	nc	37.3	18-336

Table S9. Overview of key adaptation results based on relocation at country level for the 1.5°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median and the first/third quartile (Q1-Q3).

	Relocation							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Belgium	0.0	0-16.3	0.0%	0.0%-0.1%	0.0%	0.0%-0.0%	0.0	0-0
Bulgaria	0.5	0-1.9	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Croatia	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Cyprus	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Czechia	3.0	2.3-3.7	0.0%	0.0%-0.1%	0.0%	0.0%-0.1%	0.0	0-0.1
Denmark	0.0	0-0	0.0%	0.0%-0.0%	0.1%	0.1%-0.1%	0.0	0-0
Estonia	149.5	73.5-291	0.1%	0.1%-0.1%	0.1%	0.0%-0.1%	0.0	0-0
Finland	14.3	7.1-25.3	0.0%	0.0%-0.0%	0.1%	0.1%-0.1%	0.0	0-0
France	4.6	2.5-5.8	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.1	0-0.1
Germany	4.5	3.3-6	0.0%	0.0%-0.1%	0.0%	0.0%-0.1%	0.1	0-0.3
Greece	2.0	1.5-3	0.1%	0.0%-0.2%	0.0%	0.0%-0.0%	0.0	0-0
Hungary	0.0	0-6.6	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Ireland	32.5	19.3-56.3	0.0%	0.0%-0.0%	0.1%	0.1%-0.1%	0.0	0-0
Italy	1.9	0-33.2	0.0%	0.0%-0.1%	0.0%	0.0%-0.0%	0.0	0-0.1
Latvia	4.6	2.3-6.8	0.0%	0.0%-0.1%	0.0%	0.0%-0.1%	0.0	0-0.1
Lithuania	10.6	5.7-78.2	0.1%	0.1%-0.1%	0.1%	0.1%-0.2%	0.0	0-0
Luxembourg	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Netherlands	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Poland	5.3	4.4-7.1	0.0%	0.0%-0.1%	0.1%	0.0%-0.1%	0.0	0-0.1
Portugal	6.0	3.4-8.9	0.2%	0.2%-0.3%	0.2%	0.2%-0.3%	0.0	0-0
Romania	2.1	1.5-3	0.0%	0.0%-0.1%	0.0%	0.0%-0.0%	0.0	0-0.1
Slovakia	0.0	0-1.5	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Slovenia	0.0	0-0	0.1%	0.0%-0.2%	0.1%	0.0%-0.1%	0.0	0-0
Spain	3.2	2.6-5.2	0.4%	0.2%-0.6%	0.1%	0.0%-0.8%	0.4	0.1-1.1
Sweden	4.2	3.1-5.7	0.1%	0.1%-0.2%	0.1%	0.1%-0.1%	0.1	0-0.2
United Kingdom	2.2	1.8-2.7	0.2%	0.1%-0.3%	0.2%	0.1%-0.3%	0.6	0.3-1.1
EU+UK	3.1	2.7-3.5	0.1%	0.0%-0.1%	0.0%	0.0%-0.1%	1.7	1-4

Table S10. Overview of key adaptation results based on detention areas at country level for the 2°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median (med) and the first/third quartile (Q1-Q3).

	Detention areas							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	3.0	2.2-4.8	74%	51%-86%	80%	62%-89%	62	42-118
Belgium	4.9	3.4-7.9	84%	69%-92%	87%	75%-94%	55	35-95
Bulgaria	3.0	2.3-4.4	74%	57%-87%	78%	59%-90%	17	10-26
Croatia	3.8	2.4-7.5	91%	83%-95%	94%	87%-96%	56	24-83
Cyprus	0.0	0-0	0%	0%-0%	0%	0%-0%	3	1-3
Czechia	4.3	3.3-6	83%	71%-91%	88%	78%-93%	74	53-107
Denmark	3.9	2.6-6.5	89%	75%-94%	91%	81%-95%	4	2-7
Estonia	1.3	0-2.1	16%	0%-69%	27%	0%-78%	3	0-19
Finland	3.3	2.2-5.1	61%	40%-76%	56%	42%-72%	50	25-86
France	3.6	2.7-5.6	82%	68%-90%	87%	77%-93%	450	302-767
Germany	3.8	3.2-4.9	74%	60%-86%	76%	61%-88%	280	182-425
Greece	2.8	2-4	68%	47%-81%	69%	53%-82%	11	7-17
Hungary	3.1	2.1-5.2	84%	66%-91%	86%	71%-93%	67	47-123
Ireland	2.6	2-3.9	75%	50%-88%	81%	56%-91%	22	14-35
Italy	5.2	3.7-8.1	83%	73%-89%	88%	81%-92%	168	118-270
Latvia	2.8	1.7-4.4	41%	21%-71%	48%	29%-80%	26	6-55
Lithuania	1.8	1.1-2.9	19%	1%-61%	30%	2%-70%	7	0-26
Luxembourg	4.1	2.3-7.4	83%	65%-92%	88%	76%-95%	6	3-10
Netherlands	4.4	2.9-6.5	37%	10%-59%	40%	14%-61%	10	4-28
Poland	2.4	2-3.2	64%	41%-80%	66%	46%-82%	145	83-228
Portugal	1.9	1.4-2.5	9%	3%-21%	10%	4%-16%	1	0-4
Romania	2.6	2-3.3	51%	32%-72%	57%	38%-73%	63	33-118
Slovakia	3.6	2.7-5.6	80%	61%-90%	85%	67%-92%	31	21-57
Slovenia	2.5	1.7-3.9	78%	57%-89%	82%	62%-92%	14	10-27
Spain	2.2	1.9-2.6	28%	13%-52%	34%	11%-57%	59	20-124
Sweden	4.0	2.4-6.1	71%	50%-82%	72%	56%-83%	78	46-131
United Kingdom	7.7	5.3-13.7	87%	80%-92%	88%	82%-94%	124	67-179
EU+UK	4.0	3.3-5.7	75%	65%-83%	78%	69%-86%	1957	1377-2799

Table S11. Overview of key adaptation results based on dikes strengthening at country level for the 2°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median and the first/third quartile.

	Dikes strengthening							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	2.1	1.6-3.2	57%	26%-76%	61%	27%-80%	75	33-122
Belgium	3.6	2.4-6	81%	62%-91%	85%	70%-93%	69	44-121
Bulgaria	1.8	1.4-2.5	29%	7%-51%	36%	11%-60%	8	2-23
Croatia	1.8	1.4-2.8	72%	40%-89%	79%	43%-92%	66	40-109
Cyprus	0.0	0-0	0%	0%-0%	0%	0%-0%	0	0-0
Czechia	2.5	2-3.3	63%	43%-80%	68%	47%-84%	100	59-158
Denmark	1.6	1.1-2.5	54%	11%-77%	59%	19%-84%	6	1-9
Estonia	1.6	0-2.6	58%	0%-86%	70%	0%-91%	10	0-20
Finland	2.4	1.8-3.5	44%	25%-62%	45%	27%-61%	52	20-97
France	2.7	2-3.7	67%	47%-82%	76%	58%-88%	554	348-839
Germany	3.0	2.3-3.9	66%	50%-79%	66%	52%-80%	340	210-508
Greece	1.3	0-1.8	3%	0%-38%	5%	0%-43%	0	0-13
Hungary	2.3	1.5-3.1	52%	21%-73%	53%	22%-75%	66	21-129
Ireland	1.9	1.4-2.7	52%	18%-79%	58%	24%-85%	24	9-39
Italy	2.7	2.1-3.6	68%	49%-81%	74%	57%-86%	272	171-415
Latvia	2.1	1.3-3.2	62%	29%-85%	72%	35%-91%	45	17-80
Lithuania	1.3	0-1.8	7%	0%-59%	11%	0%-63%	4	0-39
Luxembourg	3.0	1.9-6	82%	62%-92%	88%	73%-96%	6	3-12
Netherlands	3.6	2.2-6.9	41%	9%-77%	45%	13%-80%	13	6-27
Poland	1.6	1.4-2	20%	7%-45%	23%	8%-49%	68	21-178
Portugal	1.4	0-1.9	4%	0%-17%	4%	0%-9%	1	0-3
Romania	2.1	1.4-2.7	31%	7%-50%	26%	6%-46%	41	9-93
Slovakia	2.3	1.8-3.4	47%	19%-72%	51%	21%-73%	29	11-64
Slovenia	1.6	1.3-2.3	47%	15%-79%	53%	17%-83%	16	4-26
Spain	1.9	1.5-2.2	9%	4%-20%	6%	3%-20%	22	9-58
Sweden	4.3	2.9-6.7	62%	37%-74%	59%	41%-72%	66	35-111
United Kingdom	3.3	2.4-5.4	79%	67%-88%	81%	69%-89%	213	150-354
EU+UK	**2.8**	**2.4-3.8**	**60%**	**46%-74%**	**62%**	**49%-75%**	**2378**	**1551-3542**

Table S12. Overview of key adaptation results based on flood proofing of buildings at country level for the 2°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) is calculated as difference in undiscounted damage in 2100 with and without adaptation. Note that reduction in population exposed (EAPE) is not calculated (nc). Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median and the first/third quartile.

	Flood proofing of buildings							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	1.5	1.3-2.7	0.0%	0.0%-0.4%	nc	nc-nc	0.1	0-1.4
Belgium	1.6	1.3-11.6	0.2%	0.0%-12.5%	nc	nc-nc	0.7	0-48.9
Bulgaria	1.8	1.5-2.2	0.8%	0.2%-2.1%	nc	nc-nc	0.4	0.1-2.1
Croatia	1.9	1.6-2.4	0.4%	0.3%-0.8%	nc	nc-nc	0.4	0.3-2.1
Cyprus	0.0	0-0	0.0%	0.0%-0.0%	nc	nc-nc	0.0	0-0
Czechia	1.8	1.5-2.4	0.7%	0.1%-19.3%	nc	nc-nc	2.0	0.1-69.3
Denmark	1.1	0-1.5	0.3%	0.0%-1.9%	nc	nc-nc	0.1	0-0.6
Estonia	2.5	1.7-4.6	0.4%	0.2%-2.3%	nc	nc-nc	0.0	0-1.3
Finland	2.2	1.6-3.7	1.1%	0.1%-2.9%	nc	nc-nc	2.4	0.1-11.5
France	1.7	1.5-2.2	0.3%	0.1%-3.0%	nc	nc-nc	5.5	0.7-63.1
Germany	2.2	1.7-3.7	0.2%	0.1%-0.6%	nc	nc-nc	1.2	0.2-9.8
Greece	3.0	2.2-4.3	0.3%	0.2%-0.5%	nc	nc-nc	0.0	0-0.1
Hungary	1.6	1.2-2.8	0.1%	0.0%-0.8%	nc	nc-nc	0.2	0-4.2
Ireland	1.6	1.4-2	1.0%	0.3%-2.3%	nc	nc-nc	0.8	0.1-2.4
Italy	1.9	1.7-2.2	0.6%	0.3%-5.1%	nc	nc-nc	4.7	1.5-50.5
Latvia	2.1	1.6-2.6	0.5%	0.2%-2.2%	nc	nc-nc	0.4	0.1-3.8
Lithuania	2.6	1.6-9.5	0.2%	0.1%-1.7%	nc	nc-nc	0.1	0-1.5
Luxembourg	1.2	0-1.6	0.0%	0.0%-2.0%	nc	nc-nc	0.0	0-0.8
Netherlands	0.0	0-0	0.0%	0.0%-0.0%	nc	nc-nc	0.0	0-0
Poland	2.7	1.6-4.3	0.1%	0.1%-0.7%	nc	nc-nc	0.3	0.1-4.6
Portugal	4.5	3-6.3	0.3%	0.2%-0.5%	nc	nc-nc	0.0	0-0.1
Romania	2.6	2.2-3.1	1.0%	0.5%-1.6%	nc	nc-nc	1.3	0.6-5.1
Slovakia	2.1	1.4-4.3	0.0%	0.0%-0.1%	nc	nc-nc	0.0	0-0
Slovenia	2.5	1.8-4.2	0.3%	0.2%-0.8%	nc	nc-nc	0.0	0-0.4
Spain	3.0	2.6-3.5	1.1%	0.8%-13.7%	nc	nc-nc	1.9	0.9-23.4
Sweden	2.6	1.9-3.9	35%	1.1%-63.1%	nc	nc-nc	70.8	3.2-172.5
United Kingdom	2.2	1.8-2.9	12%	5.4%-42.3%	nc	nc-nc	60.4	15.8-415.6
EU+UK	**2.3**	**2-2.7**	**6%**	**1%-16%**	**nc**	**nc-nc**	**336.7**	**70-1220**

Table S13. Overview of key adaptation results based on relocation at country level for the 2°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median and the first/third quartile.

	Relocation							
Country	**BCR**		**EAD red.**		**EAPE red.**		**Costs €M/y**	
	med	**Q1-Q3**	**med**	**Q1-Q3**	**med**	**Q1-Q3**	**med**	**Q1-Q3**
Austria	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Belgium	0.0	0-19.9	0.0%	0.0%-0.1%	0.0%	0.0%-0.0%	0.0	0-0
Bulgaria	1.4	0-2	0.0%	0.0%-0.1%	0.0%	0.0%-0.0%	0.0	0-0
Croatia	0.0	0-1.1	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Cyprus	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Czechia	2.8	2.2-3.6	0.0%	0.0%-0.1%	0.0%	0.0%-0.1%	0.0	0-0.2
Denmark	0.0	0-0	0.0%	0.0%-0.0%	0.1%	0.1%-0.1%	0.0	0-0
Estonia	160.6	57.1-372	0.1%	0.1%-0.1%	0.1%	0.1%-0.1%	0.0	0-0
Finland	7.3	3.6-19.5	0.0%	0.0%-0.1%	0.1%	0.1%-0.2%	0.0	0-0
France	4.3	2.8-6	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.1	0-0.3
Germany	4.4	3.3-6	0.0%	0.0%-0.1%	0.0%	0.0%-0.1%	0.1	0-0.3
Greece	2.2	1.7-3.3	0.2%	0.0%-0.3%	0.0%	0.0%-0.0%	0.0	0-0.1
Hungary	0.0	0-11.7	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Ireland	25.5	3-43.1	0.0%	0.0%-0.0%	0.1%	0.1%-0.1%	0.0	0-0
Italy	1.8	0-21.8	0.0%	0.0%-0.1%	0.0%	0.0%-0.0%	0.0	0-0.5
Latvia	3.7	2.1-6.7	0.0%	0.0%-0.1%	0.0%	0.0%-0.1%	0.0	0-0.1
Lithuania	8.8	3.4-70.8	0.1%	0.0%-0.1%	0.1%	0.1%-0.1%	0.0	0-0
Luxembourg	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Netherlands	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Poland	5.3	4-7.7	0.0%	0.0%-0.1%	0.1%	0.0%-0.1%	0.0	0-0.1
Portugal	5.8	3.5-8.6	0.2%	0.2%-0.3%	0.3%	0.2%-0.3%	0.0	0-0
Romania	2.0	1.4-2.7	0.1%	0.0%-0.7%	0.0%	0.0%-0.1%	0.1	0-1.4
Slovakia	0.0	0-1.7	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Slovenia	0.0	0-2.4	0.1%	0.0%-0.2%	0.1%	0.0%-0.1%	0.0	0-0
Spain	3.2	2.6-5	0.4%	0.2%-0.7%	0.1%	0.0%-0.8%	0.5	0.1-1.2
Sweden	3.0	2.1-4.7	0.2%	0.1%-0.3%	0.1%	0.1%-0.2%	0.2	0-0.5
United Kingdom	2.2	1.9-2.7	0.2%	0.1%-0.3%	0.2%	0.1%-0.3%	0.7	0.3-1.4
EU+UK	**2.6**	**2-3.1**	**0.1%**	**0.1%-0.2%**	**0.1%**	**0.0%-0.1%**	**4.1**	**1-10**

Table S14. Overview of key adaptation results based on detention areas at country level for the 3°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median (med) and the first/third quartile (Q1-Q3).

	Detention areas							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	3.3	2.4-5.2	83%	69%-91%	87%	75%-93%	88	58-146
Belgium	4.8	3.3-7.8	89%	79%-94%	91%	83%-95%	82	52-123
Bulgaria	3.5	2.6-5	80%	62%-91%	82%	67%-92%	19	12-29
Croatia	4.0	2.3-7.5	96%	92%-97%	97%	95%-98%	74	32-110
Cyprus	0.0	0-0	0%	0%-0%	0%	0%-0%	3	1-3
Czechia	4.9	3.9-6.9	87%	77%-93%	90%	81%-95%	88	61-130
Denmark	4.1	2.5-6.8	92%	81%-96%	93%	86%-97%	6	3-9
Estonia	1.3	0-2.3	59%	0%-86%	74%	0%-91%	11	0-26
Finland	3.7	2.4-5.5	79%	59%-86%	76%	61%-86%	78	36-127
France	3.5	2.7-5.4	86%	75%-93%	90%	81%-95%	544	373-907
Germany	3.8	3.1-5.2	80%	63%-91%	82%	65%-92%	383	255-568
Greece	2.7	2-4.5	69%	45%-85%	69%	50%-85%	13	7-20
Hungary	3.8	2.5-6.5	92%	81%-96%	93%	85%-96%	105	60-172
Ireland	3.5	2.4-5.4	87%	72%-94%	90%	74%-95%	31	22-53
Italy	5.3	3.9-8.1	88%	79%-93%	92%	85%-95%	227	151-363
Latvia	2.8	1.8-4.1	56%	35%-77%	69%	45%-85%	39	12-68
Lithuania	1.8	1-2.5	34%	2%-71%	42%	4%-77%	10	0-37
Luxembourg	4.0	2.5-6.7	88%	78%-94%	92%	85%-96%	7	5-11
Netherlands	4.5	3.1-6.2	44%	27%-66%	48%	30%-68%	18	8-42
Poland	2.6	2.1-3.5	72%	51%-85%	75%	54%-87%	184	120-294
Portugal	1.8	1.3-2.4	7%	1%-18%	5%	1%-12%	1	0-3
Romania	2.6	1.9-3.7	63%	38%-76%	63%	44%-76%	91	41-183
Slovakia	3.9	3-6.2	87%	73%-93%	90%	79%-95%	43	27-65
Slovenia	2.6	2-4.1	82%	63%-91%	85%	65%-92%	20	14-32
Spain	2.1	1.7-2.6	33%	14%-58%	40%	13%-62%	70	26-140
Sweden	5.7	3.4-8.5	85%	73%-91%	84%	74%-92%	113	66-180
United Kingdom	9.0	6.2-14.6	93%	89%-96%	94%	90%-97%	174	96-238
EU+UK	**4.2**	**3.5-6.3**	**83%**	**74%-89%**	**84%**	**75%-90%**	**2567**	**1868-3787**

Table S15. Overview of key adaptation results based on dikes strengthening at country level for the 3°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median and the first/third quartile.

	Dikes strengthening							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	2.6	1.9-4.1	70%	51%-85%	73%	56%-87%	104	55-164
Belgium	3.9	2.6-6.8	88%	77%-94%	91%	81%-95%	91	61-153
Bulgaria	2.4	1.8-3.3	35%	18%-61%	40%	21%-69%	11	3-30
Croatia	2.1	1.6-3.5	79%	52%-92%	84%	63%-95%	81	57-119
Cyprus	0.0	0-0	0%	0%-0%	0%	0%-0%	0	0-0
Czechia	2.9	2.3-3.8	72%	54%-85%	76%	60%-88%	131	78-200
Denmark	1.8	1.2-2.7	64%	18%-83%	70%	25%-87%	8	1-14
Estonia	2.2	1.3-3.4	74%	32%-92%	81%	41%-95%	12	4-21
Finland	3.2	2.5-4.4	65%	47%-78%	68%	48%-81%	83	25-141
France	2.8	2.2-4.2	74%	57%-87%	81%	66%-91%	634	421-924
Germany	3.2	2.5-4.3	74%	58%-86%	76%	59%-87%	454	289-672
Greece	1.1	0-1.7	2%	0%-49%	3%	0%-53%	1	0-23
Hungary	3.0	2.1-4.1	69%	48%-85%	71%	53%-85%	108	55-177
Ireland	2.7	1.9-3.8	74%	55%-89%	77%	56%-91%	37	25-56
Italy	2.9	2.1-4	76%	59%-87%	80%	67%-89%	373	245-553
Latvia	2.2	1.4-3.4	71%	42%-89%	80%	49%-94%	50	24-87
Lithuania	1.6	1.1-2.1	20%	0%-65%	33%	0%-71%	9	0-46
Luxembourg	3.4	2.1-6.1	90%	79%-95%	93%	85%-97%	8	5-13
Netherlands	3.7	2.4-7.3	57%	29%-84%	64%	31%-84%	25	13-46
Poland	1.8	1.5-2.2	34%	12%-60%	38%	14%-65%	127	44-289
Portugal	1.4	0-1.9	5%	0%-16%	3%	0%-7%	1	0-3
Romania	2.4	1.8-3.4	44%	17%-64%	37%	13%-58%	77	14-145
Slovakia	2.6	2-3.6	63%	42%-81%	65%	44%-83%	49	23-83
Slovenia	1.7	1.3-2.5	57%	19%-85%	60%	23%-88%	22	9-35
Spain	1.7	1.5-2.2	11%	5%-26%	6%	3%-31%	26	9-79
Sweden	7.6	4.7-11.2	79%	62%-86%	75%	62%-83%	85	41-151
United Kingdom	4.0	2.9-6.4	88%	79%-94%	89%	81%-95%	296	202-459
EU+UK	**3.3**	**2.7-4.5**	**70%**	**59%-83%**	**71%**	**60%-83%**	**3093**	**2090-4490**

Table S16. Overview of key adaptation results based on flood proofing of buildings at country level for the 3°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) is calculated as difference in undiscounted damage in 2100 with and without adaptation. Note that reduction in population exposed (EAPE) is not calculated (nc). Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median and the first/third quartile.

	Flood proofing of buildings							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	1.6	1.4-2	0.4%	0.1%-1.3%	nc	nc-nc	1.4	0.1-7.7
Belgium	1.8	1.4-11.5	0.3%	0.0%-29.1%	nc	nc-nc	1.2	0-144.4
Bulgaria	1.8	1.5-2.4	1.5%	0.2%-16.1%	nc	nc-nc	1.0	0.1-10.6
Croatia	1.8	1.5-2.2	0.4%	0.2%-1.6%	nc	nc-nc	0.6	0.3-6.2
Cyprus	0.0	0-0	0.0%	0.0%-0.0%	nc	nc-nc	0.0	0-0
Czechia	1.9	1.5-2.4	1.7%	0.3%-49.9%	nc	nc-nc	9.1	0.9-249.8
Denmark	1.4	0-1.8	1.6%	0.0%-49.9%	nc	nc-nc	0.4	0-12.2
Estonia	2.7	1.7-5.7	0.6%	0.2%-3.1%	nc	nc-nc	0.2	0-1.9
Finland	2.4	1.7-3.7	2.0%	0.9%-33.4%	nc	nc-nc	5.3	1-58.3
France	1.7	1.5-2	0.5%	0.2%-7.2%	nc	nc-nc	11.7	2.6-194.3
Germany	2.0	1.7-2.8	0.3%	0.1%-4.5%	nc	nc-nc	4.7	0.6-78.6
Greece	3.0	2.1-4.5	0.4%	0.2%-1.0%	nc	nc-nc	0.0	0-0.5
Hungary	1.6	1.3-2.6	0.3%	0.0%-2.8%	nc	nc-nc	1.6	0-34
Ireland	1.7	1.5-2.2	2.3%	1.0%-73.1%	nc	nc-nc	3.2	1-64.9
Italy	1.9	1.7-2.1	1.2%	0.4%-23.6%	nc	nc-nc	16.2	2.8-268.6
Latvia	2.1	1.6-2.6	0.7%	0.2%-3.1%	nc	nc-nc	0.9	0.1-7.1
Lithuania	2.1	1.6-10.5	0.9%	0.1%-2.0%	nc	nc-nc	0.5	0-2
Luxembourg	1.2	0-1.7	0.0%	0.0%-3.1%	nc	nc-nc	0.0	0-1.8
Netherlands	0.0	0-0	0.0%	0.0%-0.0%	nc	nc-nc	0.0	0-0
Poland	2.1	1.6-3.9	0.3%	0.1%-1.3%	nc	nc-nc	2.2	0.1-12.2
Portugal	4.6	2.8-6.3	0.4%	0.3%-0.7%	nc	nc-nc	0.0	0-0.1
Romania	2.8	2.3-3.4	1.3%	0.7%-28.3%	nc	nc-nc	2.9	1-110.1
Slovakia	1.8	1.4-3.6	0.0%	0.0%-0.2%	nc	nc-nc	0.0	0-0.4
Slovenia	2.4	1.7-3.8	0.4%	0.2%-1.4%	nc	nc-nc	0.1	0-1.3
Spain	3.1	2.7-3.7	1.3%	0.9%-17.2%	nc	nc-nc	2.5	1-30.1
Sweden	3.5	2.2-6	68%	2.5%-76.9%	nc	nc-nc	170.3	8.2-239.4
United Kingdom	2.1	1.7-2.6	38%	6.8%-67.4%	nc	nc-nc	393.8	55.3-838.6
EU+UK	**2.4**	**2-2.8**	**16%**	**6%-30%**	nc	nc-nc	**1110**	**358-2946**

Table S17. Overview of key adaptation results based on relocation at country level for the 3°C warming scenario in 2100. The Benefit-Cost Ratio (BCR) is calculated as ratio of discounted benefits and costs over the period 2020-2100. Reduction (in %) in expected annual damage (EAD) and population exposed (EAPE) are calculated as difference in undiscounted damage and population exposed in 2100 with and without adaptation. Cost of implementation (in €million/year) reflect average of undiscounted costs over the period 2020-2100. All variables include the ensemble median and interquartile range the first/third quartile.

	Relocation							
Country	BCR		EAD red.		EAPE red.		Costs €M/y	
	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3	med	Q1-Q3
Austria	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Belgium	0.0	0-19.3	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Bulgaria	1.3	0-1.9	0.0%	0.0%-0.1%	0.0%	0.0%-0.0%	0.0	0-0.1
Croatia	0.0	0-1.3	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0.1
Cyprus	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Czechia	2.8	2-3.7	0.1%	0.0%-0.1%	0.1%	0.0%-0.1%	0.1	0-0.2
Denmark	0.0	0-0	0.0%	0.0%-0.0%	0.1%	0.0%-0.1%	0.0	0-0
Estonia	144.4	48.1-350	0.1%	0.0%-0.2%	0.1%	0.0%-0.1%	0.0	0-0
Finland	5.3	1.8-14.8	0.0%	0.0%-0.7%	0.1%	0.1%-0.4%	0.0	0-1.8
France	4.3	2.7-6.7	0.0%	0.0%-0.1%	0.0%	0.0%-0.0%	0.1	0-0.4
Germany	4.3	3-6	0.0%	0.0%-0.1%	0.0%	0.0%-0.1%	0.3	0-0.5
Greece	2.1	1.6-3	0.2%	0.0%-0.3%	0.0%	0.0%-0.0%	0.0	0-0.1
Hungary	0.0	0-10.4	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Ireland	2.8	1.8-28.3	0.0%	0.0%-0.1%	0.1%	0.0%-0.1%	0.0	0-0.1
Italy	1.7	1.2-7.1	0.0%	0.0%-0.1%	0.0%	0.0%-0.1%	0.1	0-1.5
Latvia	3.4	2.1-6.1	0.0%	0.0%-0.1%	0.0%	0.0%-0.1%	0.0	0-0.1
Lithuania	7.3	2.1-70.2	0.1%	0.1%-0.1%	0.1%	0.1%-0.1%	0.0	0-0
Luxembourg	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Netherlands	0.0	0-0	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Poland	5.7	4.3-7.9	0.1%	0.0%-0.1%	0.1%	0.0%-0.1%	0.1	0-0.1
Portugal	5.4	3.4-7.7	0.2%	0.2%-0.3%	0.3%	0.2%-0.3%	0.0	0-0
Romania	2.1	1.5-2.7	0.6%	0.0%-0.8%	0.1%	0.0%-0.1%	1.3	0-2
Slovakia	0.0	0-1.9	0.0%	0.0%-0.0%	0.0%	0.0%-0.0%	0.0	0-0
Slovenia	1.8	0-3.3	0.1%	0.1%-0.2%	0.1%	0.0%-0.1%	0.0	0-0.1
Spain	3.3	2.6-4.2	0.5%	0.3%-0.7%	0.1%	0.0%-0.9%	0.6	0.1-1.2
Sweden	2.4	1.8-3.5	0.3%	0.1%-3.1%	0.2%	0.1%-2.8%	0.6	0.1-19.6
United Kingdom	2.2	1.8-2.5	0.2%	0.1%-0.3%	0.1%	0.1%-0.3%	1.0	0.5-2.6
EU+UK	2.3	1.9-2.8	0.2%	0%-1%	0.1%	0.1%-0.2%	11.0	4-39

S3. Database of flood protection levels

Reliable information on flood protection levels is crucial for a correct estimation of river flood risk. In Europe, detailed descriptions of protection structures (i.e. type, location, geometry, design parameters) are usually available only for limited areas, while information on the design level of protection can be found for a few countries and urban areas [26,27]. Recent studies tried to overcome these limitations by developing empirical functions for estimating protection levels where information is not available. Jongman et al. [28] estimated protection levels in Europe according to modelled flood risk, assigning higher protection in areas with higher risk. The FLOPROS database [26] combined reported protection levels (based on technical reports and policy recommendations) with modelled values, interpolated at local administrative level according to gross domestic product. In several countries in Europe, these two datasets propose substantially different protection levels, especially in Northern and Eastern Europe.

The reliability of estimating protection levels through proxy variables has been questioned. A recent study carried out in United States [29] did not find any clear link between protection standards and variables such us degree of urbanization, gross domestic product, population density and land use. On the other hand, major European river watersheds such as the Rhine and the Danube maintain higher levels of protection in densely populated areas than in rural areas [28].

For the present study, we developed a new dataset of flood defence standards. The dataset leverages different sources of information on protection levels, using modelled and observed flood losses to select the most plausible protection levels for each country in geographical Europe (excluding Russia, Belarus, Ukraine, and countries in the Caucasus). The map in Figure S1 shows the distribution of protection levels across Europe.

The following set of rules dictate the hierarchal flood protection standards used in the dataset:

- Highest priority is given to design protection levels, where available from either official reports or scientific publications. To this end, we used the information collected by the FLOPROS database [26], integrated with further literature review [27].Where literature information is unavailable, the level of flood defence is determined at country scale through an inverse modelling approach, identifying the protection values that provide the closest match between modelled and available reported losses. We use the flood risk modelling framework described in this work to calculate multiple flood loss scenarios, using the two datasets of protection standards currently available for all Europe [26,28] and a range of uniform protection values at country scale.

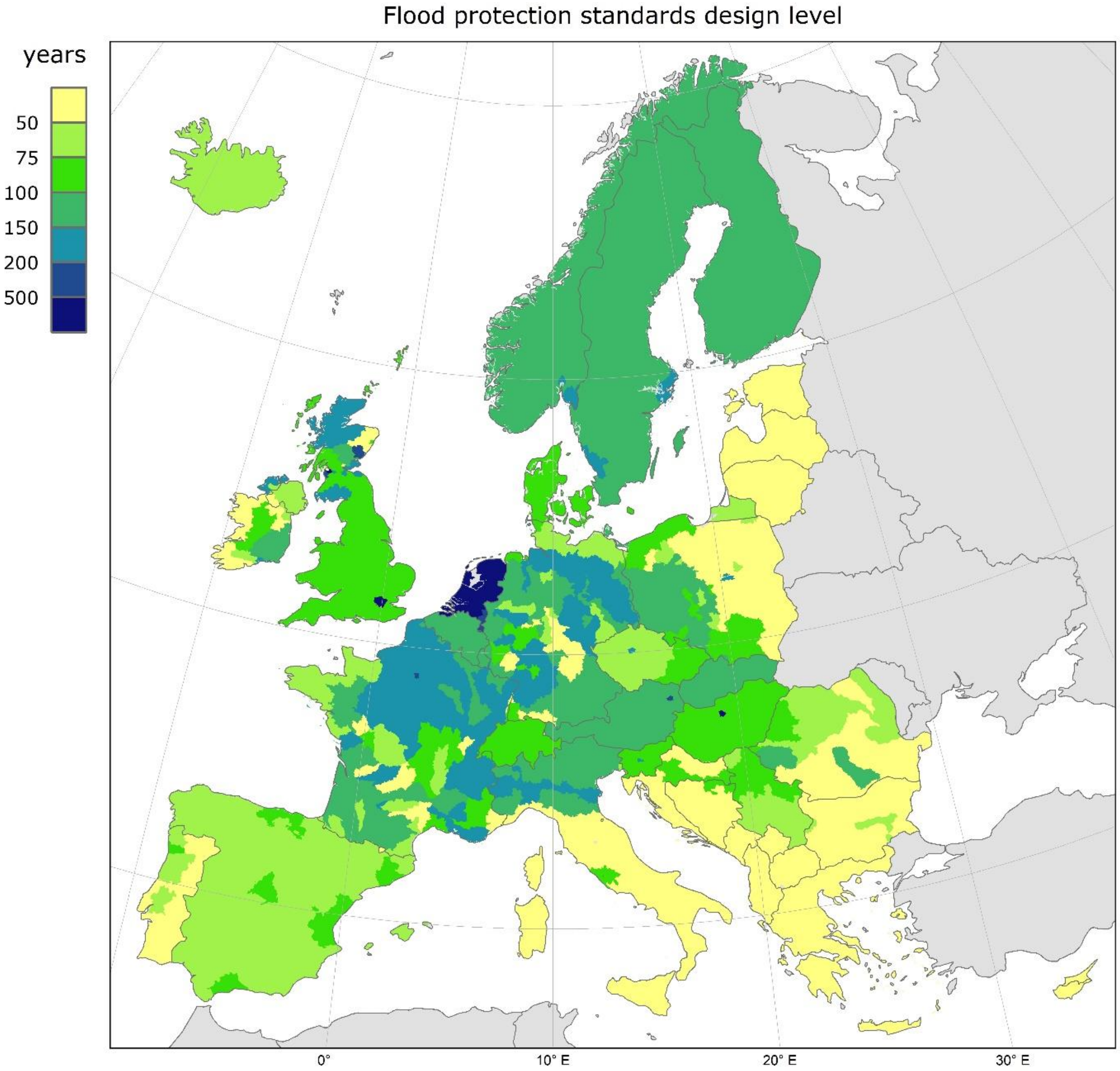
  - In countries where national-scale flood loss assessments are available (either from technical reports, scientific publications, or loss datasets such as EM-DAT [30], the NatCatService [31] and HANZE [32]), we selected from the multiple flood loss scenarios the protection values that provide the closest match with national-scale flood losses;
  - In countries where all modelled flood loss scenarios exceed 200% of reference loss data (see Section S4 and Figure S2), we used a uniform national value between 50 and 150 years. This range reflects the standards reported in literature [26,27]. Design and/or legally defined protection levels are often set to at least 100-year return period at country scale (e.g. Austria, Hungary, Netherlands) and in areas around large rivers (e.g. Sava and Danube in Croatia and Serbia; Po in Italy). Higher protection standards are reported for the Netherlands and in some major urban areas (e.g. Budapest, Hamburg, London, Vienna), and protection values below 50-year return period are seldom reported. As such, we did not use protection levels higher than 150 years to avoid unrealistic values in countries where modelled losses are far from reports (e.g. Scandinavian countries), or where few reported data are available (e.g. Estonia, Latvia and Lithuania) .

Note that the selection of protection levels is carried out at the country scale because flood losses from observations are mostly reported at national level.

S4. Reliability and uncertainty of the modelling components

Modelling present and future river flood impacts at continental scale requires inevitable simplifications, which limit the accuracy of results. Furthermore, there is substantial uncertainty pertaining to models and datasets representing hazard, exposure and vulnerability, especially when used for projecting future scenarios [33]. Alfieri et al. [34] applied a modelling framework comparable to the present work to model the impacts of major flood events that occurred in Europe since 1990, and found that recorded impacts could be adequately reproduced. However, they did not investigate in detail the skill of the single modelling components. In this Section we discuss the main sources of uncertainty of the modelling framework, we review previous validation exercises of the modelling components, and we present additional validation analyses regarding economic losses.

Figure S1. Distribution of flood protection levels across Europe, expressed as maximum return period of the design flood (in years). Countries not included in the analysis are depicted in grey.



Flood hazard maps

The river flood hazard maps have been evaluated using official hazard maps for Hungary, Italy, Norway, Spain and the United Kingdom [18]. Modelled maps could identify on average two-thirds of reference flood extent, however they also overestimated flood-prone areas for flood probabilities below 1-in-100-year, while for return periods equal or above 500 years the maps could correctly identify more than half of flooded areas. Overall results were comparable to existing large-scale flood models when using similar parameters and conditions for the validation. Dottori et al. [18] identified different shortcomings of the modelling framework, such as the absence of flood protections and limited topographic detail for river channels and low land areas.

Climate and hydrological projections

The use of an ensemble with 22 climate projections aims at characterizing the overall climate uncertainty in the hydrological simulations [35]. However, the ensemble might still underrepresent the real uncertainty of future climate scenarios [36]. Other factors such as the bias correction of climate projections and the spatial resolution of the input data may influence results though probably to a smaller degree [16]. In this work we used a single hydrological model for all future projections, namely the LISFLOOD model. Using an ensemble of hydrological models might better represent the uncertainty of future hydrological changes, since previous research [17,18] showed that future streamflow and inundation projections are significantly affected by the choice of hydrological and flooding components.

The skill of the LISFLOOD model in reproducing observed flow regimes has been extensively tested by [37] and is summarized in [18]. These authors observed that the difference between empirical and modelled distributions of annual discharge maxima is generally below 25% for the gauge stations used for calibration and validation. A lower model skill was observed in areas characterized by the presence of several reservoirs, dams and other flow control structures. Reservoir parameters are calibrated in LISFLOOD to improve reproduction of observed outflows. Yet, in Europe only a minority of dams (less than 10%) are exclusively or partially designed for flood control [38] and therefore the operating rules might significantly diverge from those simulated.

Exposure and vulnerability data

The accuracy of exposure data have been tested in previous studies [39,40,41], however the 100m resolution used might be insufficient to characterize population and asset exposure in some areas [42].

Methods for evaluating economic losses due to floods are a key source of uncertainty in evaluating flood impacts [43]. Huizinga et al. [21] observed that the potential uncertainty of flood damage functions can exceed ± 50%, although this value is in line with the typical accuracy of damage models [43]. This is further exemplified by previous applications of damage functions that showed mixed performances when compared with observed damages [44,45].

Flood protection standards

Flood protection standards are possibly the most relevant source of uncertainty in large-scale modelling exercises [46]. In the present study we have developed a database combining reported and modelled protection levels from different sources (see Section S3). However, the overall confidence about flood protection estimates is highly variable across Europe, and in particular it is lower in Eastern Europe countries due to the lack of information.

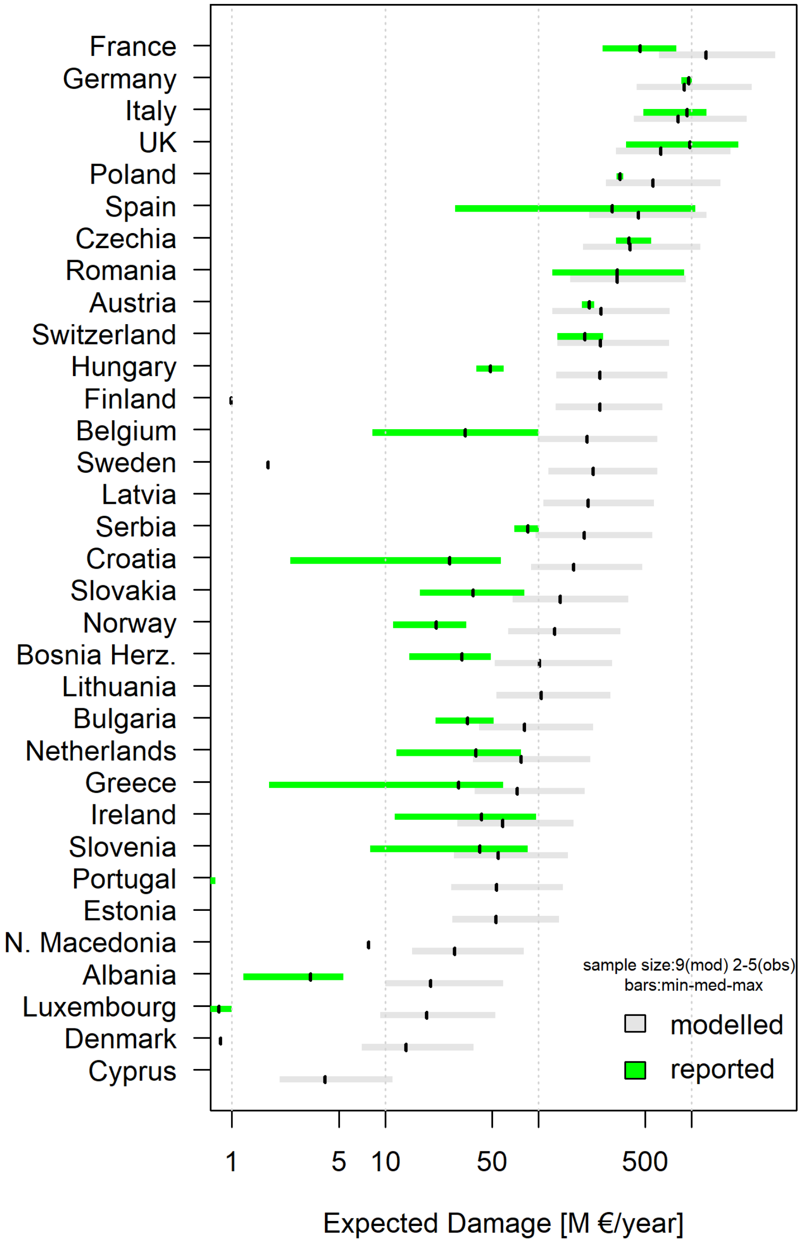
In Figure S2 we provide a further evaluation of country-scale results by comparing modelled annual average economic losses against reported losses. Uncertainty ranges of reported losses in Figure S2 are given by the minimum and maximum reported value for each country (available in Table S18), while for modelled losses we report the minimum and maximum values of the sensitivity analysis described in Section S1.

We find that in several countries modelled loss estimates are comparable with reported losses, taking into account the uncertainty bounds of both (i.e. the median values of modelled losses fall within the uncertainty bounds of reported losses). In total, these countries account for more than 60% and 85% of, respectively, overall modelled and reported losses. Notably, modelled losses match observations in most countries where national-scale protection values are based on reported data (Austria, Netherlands, United Kingdom, with the exception of Hungary). This fact suggests that the risk modelling framework is able to reproduce actual flood losses, within the limits of continental-scale datasets. Our estimates are also in line with available country-scale risk assessments based on independent models and data. For instance, [62] estimated for Germany a median EAD of 530 million €, with an uncertainty range of 245-940 million €.

Table S18. Comparison of modelled flood losses (median value) against reported data from national reports (see references in each row) and loss datasets (HANZE [32]; EM-DAT [30], the NatCatService [31]). All losses are expressed in million € (actualized to 2015 value).

Country	Loss datasets (1990-2015) [M€]			National loss reports [M€]	Modelled losses – median [M€]	References for national loss reports and notes
	HANZE - river	NatCat Service	EM-DAT			
Albania		5.3	1.2		21	
Austria	220.4	232.0	193.1		260	
Belgium	11.7	13.0	8.2		209	
Bosnia-Herzegovina		48.9	14.5		109	
Bulgaria	21.3	51.0	31.2		87	
Croatia	19.4	57.3	2.4		188	
Cyprus		0.2	0.0		4	
Czech Republic	324.0	332.8	321.8	433-546	412	[47,48]
Denmark	0.0	2.5	0.0		15	
Estonia	0.0	0.0	0.0		58	
Finland	0.6	0.9	0.0	2.5	272	[49]
France	262.1	270.3	265.3	664-800	1288	[50,51,52] (all types of floods)
Germany	859.9	1011.1	1001.4		922	
Greece	1.8	29.5	59.0		81	
Hungary	59.7	47.1	39.5		274	
Ireland	12.4	49.0	11.6	97	62	[53]
Italy	484.7	1250.7	1075.8		887	
Latvia	0.0	0.0	0.0		227	
Lithuania	0.1	0.0	0.0		112	
Luxembourg	1.0	0.9	0.5		20	
Montenegro		0.5	0.0		16	
Netherlands	11.9	76.9	28.9		79	
North Macedonia	0.0	12.3	11.1		31	
Norway	26.6	14.3	11.2	34	133	[54]
Poland	325.2	342.4	340.9	359	581	[55]
Portugal	0.6	0.2	0.8		57	
Romania	123.4	156.7	132.4	894	340	[56]
Serbia		69.5	101.0		202	
Slovakia	17.5	34.6	16.9	81	142	[57]
Slovenia	59.1	13.3	8.0	86	59	[58]
Spain	28.7	70.0	60.2	1059	452	[59] (all types of floods)
Sweden	3.4	1.8	0.0		244	
Switzerland		207.1	132.8	265	279	[60] (floods - debris flows)
United Kingdom	375.6	622.5	870.3	2028	676	[61] (coastal - river floods)

Figure S2. Comparison of modelled and reported average annual losses at country level. Bars indicate minimum-maximum range and median value. Sample size of modelled losses: 9; Sample size of observed losses: 2-5 (see Table S18 for the values for each country).



Conversely, losses appear largely overestimated (i.e. more than 100%) in France, in Scandinavian countries (Denmark, Sweden and Finland), as well as in several medium-small countries (e.g. Belgium, Bulgaria, Croatia, Latvia, Lithuania). While the mentioned limitations of the modelling framework can explain the gap between modelled and reported data in these countries, it is important to note the differences between loss data from different sources. On the one hand, national-scale studies in Table S18 report larger losses than European and global scale datasets. A comparison of national disaster loss databases with global loss data showed that total losses can be up to 60% higher, due to the fact that extensive losses from high-frequency, low-severity events are not accounted for [63]. This suggests a lower confidence of risk estimates where no national loss data are available. On the other hand, some national loss reports include impacts due to flash floods, coastal floods or dike failure events, which are not considered in our modelling framework. Where possible, we considered only reported losses attributed to river flooding. In Southern and Central European countries such as France, Greece, Italy and Spain, the contribution of flash floods to overall flood impacts is considerable and might equal the share due to river floods [32].

Accurate modelling of historical loss data is further complicated by the temporal and spatial variability of risk components over the period of observations [32], whereas modelled losses assume fixed exposure and vulnerability. In addition, reported losses refer to specific time periods, so the estimated average annual loss is influenced by the frequency of events that can vary significantly depending on the period. Finally, our modelling framework does not consider the possibility of failure of protection measures.

Modelling of adaptation measures

The outcomes of the adaptation analysis are sensitive to the modelling assumptions used in the design of adaptation measures, and to the parameters used to determine costs and benefits of the different measures, which vary widely among studies (Table S2). For instance, descriptions of flood proofing measures report variable costs according to the type of measure (e.g. wet or dry proofing, elevation), the attainable damage reduction and the level of hazard (e.g. protection up to 1m of water depth). More accurate analysis could be carried out considering separately different flood proofing measures in view of local hazard and exposure characteristics. Yet, the limited number of empirical studies available from literature and the accuracy of continental-scale data still restrict such analyses to local scales [14,64].

We base the design of detention areas on considering only available floodplain storage and flood volumes. However, other factors influence the hydraulic behaviour of a detention area, such as the shape and magnitude of the flood hydrographs, and the tributary conditions both upstream and downstream of the detention area. Therefore, the design of detention areas would require simulating multiple scenarios with variable spatial and temporal distribution of flood waves [65,66,67]. Also, some floodplains might already be used as detention areas, as it is the case for the Sava River Basin [68] and the Netherlands [65], or might be a protected natural area (e.g. Natura 2000 network, https://ec.europa.eu/environment/nature/natura2000/index_en.htm). Additional factors such as the ratio between overall storage volume and storage area influence the effectiveness of retention and detention areas.

Different studies report higher costs of raising dykes in urbanized areas than in rural areas, as available spaces are reduced [4]. Moreover, the simplified approach used to design dike heightening and detention areas cannot fully reproduce their interaction with existing flood control structures. For instance, heightening dikes upstream might increase the magnitude of flood waves downstream, thus reducing the effectiveness of flood protections and altering the functioning of structures such as in-line reservoirs. On the other hand, it is important to note that changes of stream flow regime under future climate will modify as well the operating rules and conditions of existing structures. For relocation, implementation costs are largely dependent on building parameters (e.g. number of dwellings and storeys, market value of acquired land and relocated buildings) which are not available at EU scale.

Even though we cannot explicitly validate the risk reduction rates calculated for the adaptation measures, the findings of recent research works are broadly consistent with the results of our analysis. Farrag et al. [69] evaluated the role of floodplain storage in attenuating flood peaks along the German part of the Rhine River. The authors considered a 10,000-year synthetic flood time series under present-day climate conditions, and used a detailed 1D-2D hydrodynamic modelling framework to simulate the effect of uncontrolled floodplain storage consequent to levee overtopping. The modelling framework of [69] differs in some aspects with our analysis of risk reduction based on floodplain detention areas. Still, they found an overall risk reduction by over 50% over the simulation period, which is well comparable with the median EAD reduction of 66% (50%-81%) found in our study for the whole Germany under the 1.5°C warming scenario.

Previous studies confirmed that cost-efficiency of building-based damage mitigation measures depends strongly on the flood probability faced by households. Richert et al [14] recommended dry-proofing measures and elevating buildings only for dwellings that are exposed to floods with a return period lower than, respectively 100 years and 30 years. Similarly, [64] reported that some flood damage mitigation measures are cost-effective in areas with flood frequencies up to 1-in-50-year. Such indications are consistent with the outcome of our analysis, that is, flood-proofing of buildings becomes more economically attractive as climate change increases flood frequencies [64].

Cost-benefit analysis

The cost-benefit analysis (CBA) applied here is based on several assumptions that have to be considered to better understand the outcomes.

We based the analysis on optimizing each adaptation measure separately at NUTS2 region level (DS and RA measures) or over a 5km grid (FP and RE measures). On the one hand, using uniform design levels may be not ideal since exposure can be highly variable within each NUTS2 and 5km region and therefore protection measures may be needed only in certain parts of a region, such as in urban and densely populated areas. This is especially true for measures based on exposure and vulnerability reduction (i.e. relocation and damage reduction measures), for which cost/benefit analysis can be applied even at building scale. For instance, a recent analysis carried out in United States found an average benefit-cost ratio of 6.5 for targeted relocation of residential houses [69], whereas we considered for relocation all built-up areas located within the 1-in-500-year flood extent.

On the other hand, the resolution of data and models applied in this study is strongly limited by the continental scale of the analysis. For instance, additional tests considering relocation only for built-up areas located within the 1-in-50-year flood extent did not show significant changes at European and country scale in terms of cost-benefit analysis.

Moreover, having different protections standards for nearby regions may pose problems in the implementation of measures based on hazard reduction (i.e. dykes strengthening and detention areas), which require more uniform levels of protection along the river network.

We evaluate benefits as the reduction in expected annual economic damages, meaning that low-probability/high-consequence events and high-probability/low-consequence events have the same weight if the expected impact is the same. This risk-neutral approach disregards any possible risk aversion of societies, that is, the willingness to avoid high-consequence events, for instance by paying risk insurance premiums [71].

Furthermore, we assume a constant value of money across society, whereas damage has a larger impact on welfare of lower-income population [71]. Using property damage as a metric for evaluating adaptation benefits systematically favours interventions in wealthier, densely populated areas over rural and less developed areas, because avoided damages are greater [72]. We also do not consider differences in social vulnerability, which greatly influences the capacity of households to adapt and respond to floods [73]. Indeed, different studies observed an uneven distribution of water related risks shaped by socio-political structures in the Netherlands [73], South Africa [74] and the United States [75].

These assumptions (risk neutrality, constant value of money and constant vulnerability across society) can be considered acceptable assuming that both costs and benefits are typically largely covered by national governments, for instance through compensation of flood losses and investments in flood protections [71]. This is consistent with the current risk management policies of different European countries, although each country uses different criteria regarding insured losses, liability for damages and refunding policies [76]. It is important to note that CBA methods can be modified to account for risk aversion and social vulnerability, so further research could focus on these issues [77].

Our CBA analysis only provides a qualitative assessment of the environmental costs and benefits of adaptation measures, and impacts on cultural heritage and critical infrastructures and buildings are not considered. Also, socio-economic projections are independent from flood risk projections, therefore we cannot simulate maladaptation effects such as increased development in floodplains caused by increased protection. Moreover, the reduction in population exposed is not monetized in the cost/benefit analysis, due to the lack of accurate information on impacts (both physical and social) and sensitivity issues in attributing economic value to human lives [78]. It is important to note that in some countries the protection of people is prioritized over economic convenience. For instance, Austria and Germany ensure the same flood protection design everywhere according to [76]. The use of methods such as multi-criteria analyses and robust decision-supporting approaches [78] may allow for the inclusion of non-monetary impacts in risk assessment.

The outcomes of the CBA analysis are also sensitive to discounting, which gives more weight to present capital costs and downgrades the benefits that will mostly come later in the century. We used discount rates in line with the EC Guide to Cost-Benefit Analysis of Investment Projects [79] that were assumed constant in time. We did not analyse the effect of higher discount values because adaptation measures must necessarily be designed for long-term effects, and thus are penalized. Using lower or time-declining social discount rates results in higher cost-effectiveness of all the measures and supports the view that we should act now to protect future generations. As such, in the article we compare impacts under present and future scenarios using undiscounted economic values, in order to highlight the impact reduction provided by the different adaptation strategies [79]. Similarly, adaptation measures are optimised considering the most likely river flow projections in 2100 under the 1.5°C, 2°C and 3°C warming scenarios. Decision makers could select a more conservative criterion and aim to protect against the high-end, less probable future extreme river flows. This would require higher investments but imply less risks for future generations.

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